PRESSURE DROP STUDIES ON STRATIFIED TURBULENT FLOW OF TWO IMMISCIBLE LIQUIDS

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CERTIFICATE

It is certified that this work has been carried out under my supervision and that this has not been submitted elsewhere for the degree.

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ABSTRACT

In this thesis stratified flow of two immiscible liquids - water and kerosene is studied when the flow of both the phases are in turbulent regime. The pressure gradient is measured in a 0.624 inch glass tube. And the effect of temperature on two phase pressure gradient is also studied.

It is observed that as we increase the temperature, the viscosity of liquid decreases, though to a small extent, there is little effect on pressure gradient when the flow is turbulent stratified. Taking the data at higher temperatures (which is not possible in the present case due to the hazardous nature of kerosene) would have shown that liquid-liquid flow case would yield results similar to gas-liquid case, under conditions of low liquid viscosities. The Lockhart and Martinelli curves would then nearly represent the combined pressure drop.

In the present case it is observed that there is a maximum deviation of 60% from Lockhart and Martinelli's (turbulent-turbulent) curves for liquid-gas flow.

It is concluded that actual pressure drop is very less than the predicted values by curves for liquid gas turbulent-turbulent system. Hence the curves for liquid gas system are not valid for liquid-liquid system in the

turbulent regime. The two phase pressure gradient for liquid-liquid system can be predicted by the equation

$$\phi^2 = B_o + B_1(X^2) + B_2(X^2)^2 + B_3(X^2)^3$$

As ϕ^2 is ratio of two phase pressure gradient to pressure gradient when phases are flowing alone and X^2 is ratio of pressure gradient when more viscous flowing alone to the pressure gradient of less viscous flowing alone. B's are constants.

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CONTENTS

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CHAPTER 1

INTRODUCTION

The contact of two immiscible liquids is encountered widely in chemical and petroleum industries. The design of tubular reactors, liquid-liquid extraction equipments and pipelines for the liquid transportation may depend on the knowledge of flow characteristics of the simultaneous movement of immiscible liquids. Although there is a considerable amount of published information on the flow of liquid gas and liquid solid mixtures, there is little on the flow of liquid-liquid mixtures[1,5,9].

One of the more interesting and potentially useful phenomena associated with the simultaneous, horizontal pipeline flow of two incompressible fluids is the fact that the pressure gradient and power requirement[1,13] necessary for the flow of the more viscous phase at a given rate may be substantially reduced by the presence of the less viscous phase. The most common practical example in which this effect is evident is the pipe line flow of petroleum and water[4]. And this reduction of power is more pronounced when it is possible to overcome

the tendency of two liquids to stratify and to produce a flow in which the entire surface of the pipe is in contact with less viscous phase.

Stratified flow was observed by number of workers for flow of oil and water in a horizontal tube(2,5,9), this can be with or without interfacial waves. And interesting results were observed with respect to phase stability and interfacial structure. Also stratified flow pattern was observed for both phases laminar,-laminar, laminar turbulent and turbulent-turbulent.

The usual approach to the analysis of turbulent stratified flow(9) system is exemplified by the work of Hanratty(11) and Shearer(12) for gas liquid system. Attention is focussed on one phase which is moving faster to determine the drag effect. The fluid velocity in this phase is assumed to follow a logarthmic distribution from which an equivalent interfacial roughness parameter is deduced on the basis of velocity profiles or pressure drop data. This approach is fairly successful when applied to the system in which the phase velocities and phase depth are of different magnitude and since velocity distribution in the slower phase can be ignored, if laminar, and has a small perturbing effect upon the profiles of the faster phases.

In the present work, two immiscible liquids - water and kerosene - are studied for the stratified turbulent-

turbulent flow in an 0.62 inch tube. Pressure drop data for stratified (turbulent - turbulent) flow in pipes is being correlated in terms of Lockhart and Martinelli parameters[7].

Effect of temperature on the pressure drop of two phase flow is also analysed in terms of Lockhart and Martinelli parameters. The two phase pressure gradient for liquid-liquid system is predicted by a mathematical equation.

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CHAPTER II

A REVIEW OF EARLIER INVESTIGATIONS

There is quite a lot of work done on flow of two immiscible fluids in a pipe line and rectangular conduits in the last decade, but lack of understanding of the mechanism of the interaction between two flowing phases has been clearly pointed out by number of workers. A brief review of some of their studies is presented in this chapter.

Charles, Govier and Hodgson[1] studied the factors effecting the transport of crude oil with the help of water in pipe lines. They came up with the conclusion that addition of increasing amount of water to oil which is originally in laminar flow lowers the pressure gradient to a minimum, after which the addition of more water increases the pressure gradient, and with sufficient water, the pressure gradient exceeds the pressure gradient for oil flowing alone. And as we know that minimum pressure gradient leads to less power requirement necessary to pump a given quantity of oil. This is due to the fact that by addition of controlled quantity of water to a viscous crude oil leads to a concentric flow of oil and water. As water, which is less viscous forms a annulus

in the region of high shear rate next to the pipe. As they studied different viscosity oils and flow pattern showed dissimilar behaviour at high input rates. They concluded, that this was due to different oil water interfacial properties.

To evaluate the magnitude of pressure gradient reduction to be expected in stratified flow system, Charles and Redberger[2] solved the Navier-Strokes equations by a numerical procedure using a digital computer, for laminar stratified flow of two Newtonian liquids (oil and water) in a circular pipe. They found out that maximum value of pressure gradient reduction factor ranged from 1.12 to 1.31 for different viscosity of oils.

These computed reduction factors were considerably lower than experimental values and this shows that wave motion and mixing at the oil water interface produces a very significant reduction in the pressure gradient.

But Gemmell and Epstein[3] found out that, when theoretical results for laminar flow obtained by them, were compared with experimental data of Russell, Hodgson and Govier[1] for horizontal flow of mineral oil and water in circular pipe. Good agreement was obtained for both holdup and pressure drop data when both oil and water were in laminar flow. As water entered the transitional and turbulent regions,

however, a deviation between the experimental and the computed results developed. The deviation increasing in the anticipated direction as the Reynold number of water is increased. They concluded, that this was due to the fact that the maximum pressure gradient reduction factor was between 25% and 65% and flow of water was turbulent and oil laminar. A general expression for velocity distribution was derived by Charles and Lilleleht[4] with the assumption that there is no slip at the wall and interface. They obtained good agreement with experimental results for laminar-laminar flow but significant deviations for turbulent regions. This was due to the interfacial velocities becoming apparent.

Charles and Lilleleht[5] investigated for oil in laminar and water in turbulent flow experimentally and also studied stability and interfacial waves in co-current flow. They used a rectangular transparent conduit 1" x 8" cross-section and oil, water viscosity and density ratio was 5.33 and 0.82 respectively. Observations resulted in different type of interfacial structure as the Reynold number was increased. When both oil and water was laminar the region was characterised by a completely smooth interface. As the water flow rate is increased turbulent patches were observed. Coincident with the appearance of turbulent patches, the interface waves were observed to be disturbedby two dimensional waves i.e. waves having crests normal to the direction of the

flow and several times longer than the wave length. At low Reynolds number of oil and high water flow rate, very large and regular two dimensional waves appeared with crests running across the channel. Further increase of water Reynold number and oil flow rate results in additional thinning of oil layer and in the appearance of roll waves. These waves move relatively slowly. When both phases are turbulent the waves become more and more three-dimensional in character with crest length approximately equal to the wave length.

Charles and Lilleleht(6) found a correlation of pressure gradient for stratified laminar-turbulent pipe line flow of two immiscible liquids. The parameters introduced by Lockhart and Martinelli*(7) to correlate pressure gradient accompanying the flow of gas-liquid mixtures in horizontal pipe have been found useful in correlating data for stratified flow of two immiscible liquids in laminar-turbulent regions. Curves for liquid-liquid data available from three different sets of experiments, though being significantly displaced from Lockhart and Martinelli curves for liquid gas systems, represents the data with a maximum deviation of approximately

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*Dukler, Moye and Cleveland(8) showed in their paper that for two phase flow of fluids Lockhart and Martinelli's correlation, oldest of the five tested (Baker; Bankoff, Chenoweth, Yagi and Lockhart and Martinelli) shows the best agreement with a set of carefully taken experimental data on pressure drop.

24%. This deviation was due to the fact that for all experiments ϕ_M^2 is greater than one i.e. the two phase (laminar-turbulent) pressure drop in general exceeds the pressure drop for the flow of more viscous phase alone.

Ron Darby and W.W. Akers[9] studied velocity profile data for both phases of cocurrent stratified flow system of two immiscible liquids-water and kerosene - in turbulent regime. The equipment used for experiments consists of a transparent plastic channel 15 ft. long and 11½" x 2½" cross-section. A separate recirculating system was provided for the phases.

The usual approach to the analysis of turbulent stratified flow system is exemplified by the work of Hanratty[11] and Shearer[12] for gas liquid system. Attention is focussed on one phase which is moving faster to determine the drag effect. The fluid velocity in this phase is assumed to follow a log distribution from which an equivalent interfacial roughness parameter is deduced on the basis of velocity profile data. The velocity profile data was correlated by a method which combined Pai's results for flow between parallel plates. The method yield values for both wall and interfacial drag coefficient which correlated with flow properties of two phase. All dependent parameter except interfacial shear resulted in symmetrical correlation. Interfacial drag was found to depend

primarily upon the flow intensity of the upper phase and upon which is moving faster.

The interfacial shear was defined as

$$\bar{f}_{i1} = \frac{(\frac{1}{2}\rho_1 \bar{U}_1^2 f_{i1}) + (\frac{1}{2}\rho_2 \bar{U}_2^2 f_{i2})}{(\rho \bar{U}^2)_1}$$

where $\bar{f}_i$ - integrated mean drag coefficient at interface

$\bar{U}$ - integrated mean velocity, ft./sec.

ρ - density lb./ft.^{3}

U - time averaged velocity ft./sec.

1 - phase 1

2 - phase 2

i - interface

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CHAPTER III

EXPERIMENTAL

A. Experimental Set-up:

The experimental set up for study of two phase flow of two immiscible liquids - water and kerosene - was designed, fabricated and assembled. It consists of 0.62 inches I.D. glass tube with two pressure taps 4 ft. apart. For storing and pumping oil and water two galvanized tin drums of 50 litres capacity were taken. To pump water a rubber impeller, 3/4 HP, centrifugal pump and for kerosene oil a 1 HP centrifugal pump were used. Rubber impeller is used for water as it is heated to higher temperatures. As water flow rate is varied over a wide range, a 1 inch bypass line is used while for oil a 1/2 inch pipe is fitted. An orifice plate, which has a carefully drilled 1/4 inch diameter hole concentric with 1/2 inch pipe is mounted on both oil and water line with the help of flanges as shown in Fig. 1. The 5 ft. long glass tube is connected between two flanges with the help of flexible tubes in order to avoid breaking of tube. Water and oil mixture enter tube from a $1\frac{1}{2}$ inch diameter and 1 ft. long

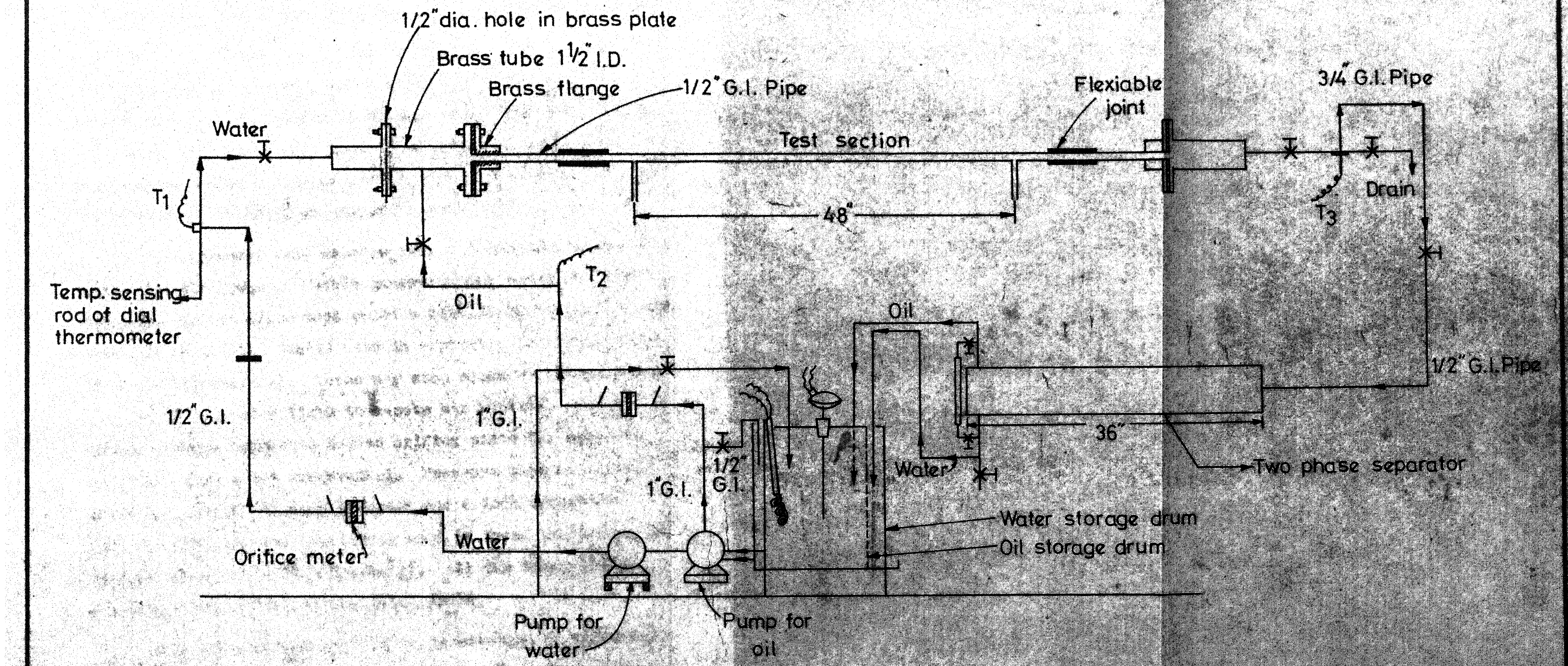

Fig.1 - Experimental setup for two phase flow of liquids.

brass tube in which the oil and water enter separately. As shown in Fig.1, after passing the test section the mixture is separated in a cylindrical Aluminium tank, which is 6 inch in diameter and 3 ft. long and is kept horizontally above the storage drums. Length and diameter of this tank is such that a perfect phase separation occurs and oil leaves the tank to storage oil drum from top and water from the bottom to its storage drum. The system was such that both the oil and water are completely recovered, but some make-up oil and water were to be added at times.

For pressure drop measurement, a U-tube manometer is used. The two limbs of U-tube manometer are connected with pressure taps on glass test section with flexible 1/4 inch OD. transparent tubes. Liquid used in manometer is carbontetrachloride (Appendix A). Three way stop cocks are attached on the top of manometer limbs to remove air bubbles. U-tube manometers are connected across orifice plate for both oil and water flow rates measurement. Pressure taps on orifice plate are located $1\frac{1}{2}$ inch upstream and 4 inch downstream from the orifice. And the liquid used in these manometers is mercury (Density = 13.4 gm./cm^3.). All the three U-tube manometers are fitted on the panel board.

As the pressure drop is to be measured at different temperatures, heating of water is done in the water storage drums. It is heated by a 2 KW immersion heater. The oil

cannot be heated directly as its minimum flash point is 115°F (46.5°C). The temperature of oil and water inlet streams are measured by a dial thermometer. This type of thermometer has a temperature sensing rod which is fitted in the pipe with the help of pipe fittings and a special 1/2 inch brass pipe fitting. Temperature of stream (mixture) after the test section is also measured by dial type thermometer. Another thermometer measures oil storage drum temperature. The temperature of both oil and water should be equalised. This is achieved by having a temperature sensing device (resistance type) in water tank connected to a relay which in turn is connected to a temperature recorder - controller. The relay is also connected to the immersion heater as shown in the circuit diagram (Fig. 2). The temperature recorder-controller is mounted on the panel board and any desired temperature can be adjusted. After the desired temperature is reached the power to the immersion heater is switched off automatically.

B. Pressure Drop Measurement:

In this work the effect of temperature on pressure drop data of two immiscible liquids - water and kerosene - flowing in an 0.62 inch glass tube as stratified, turbulent-turbulent flow is studied. The data obtained is correlated in terms of Lockhart and Martinelli's parameters[7]. The studies were made at four different temperatures (20°C, 30°C,

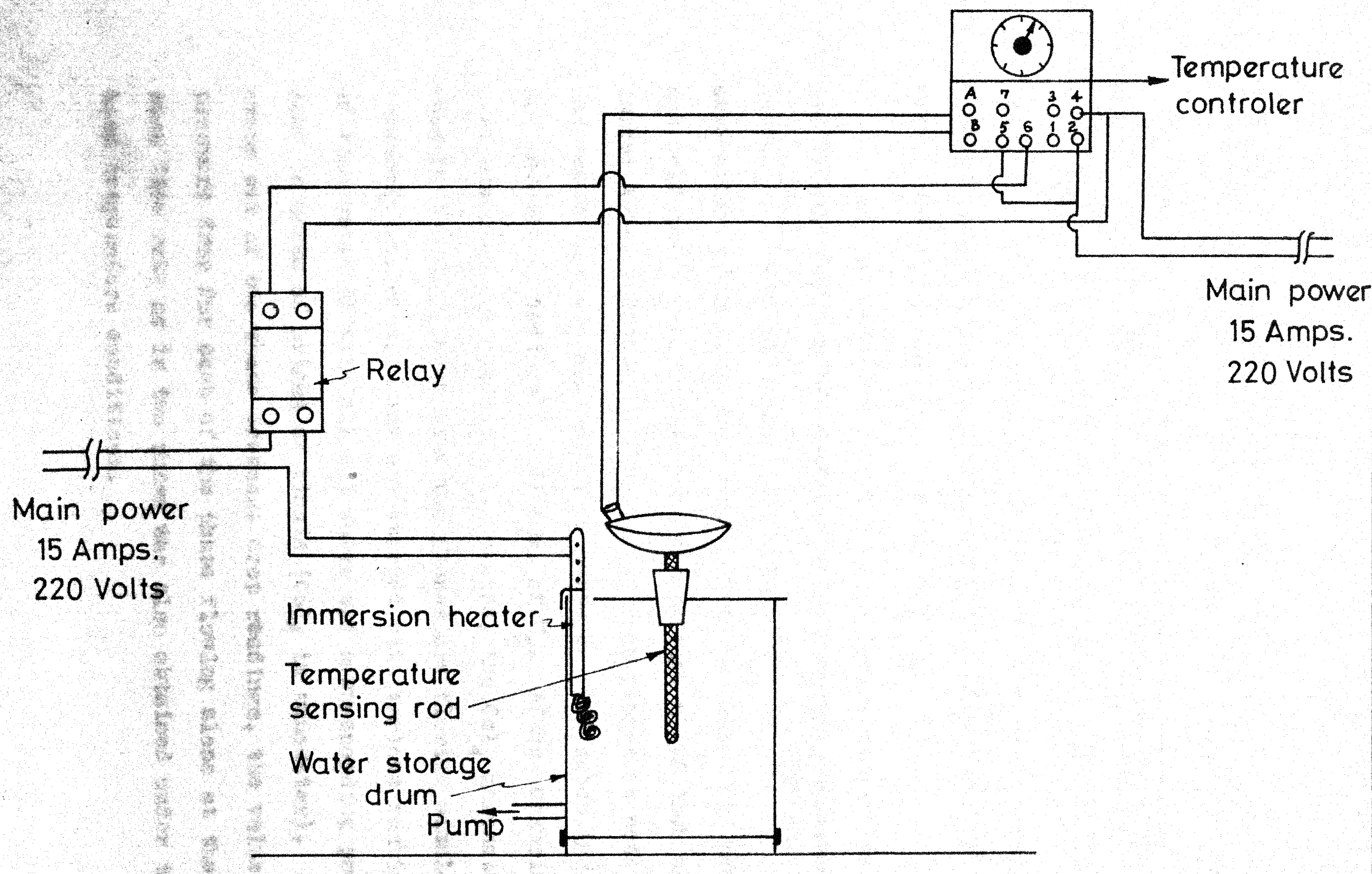

Fig. 2- Circuit diagram for temperature control in water storage drum.

40°C and 50°C). Higher temperatures were not considered as the minimum flash point for kerosene is 46.5°C. Therefore it will be hazardous to use kerosene above minimum flash point.

Before starting the readings, the temperature is maintained constant with the help of the temperature recorder-controller. Further the temperatures on all the dial thermometers should be same (error acceptable: $\pm$ 1°C).

Air bubbles from all the three U-tube manometers are removed and initial readings of each of the manometers is noted. The storage drums should be full and the two phase separating cylindrical drum should also be full, half water and half oil. This can be observed through a 1/4 inch transparent level indicator. Also the orifice plates on both oil and water line are calibrated in terms of flow rates (gm./sec.) and manometer readings (Δ H) cms. of H_g. After ensuring that steady-state condition is reached, the Ccl_4 manometer reading (ΔH_{TP}), when both the phases are flowing simultaneously was read. Runs are started with various combinations of flow rates of both oil and water and corresponding pressure drop in terms of height of liquid (Ccl_4 in manometer). For every set of two phase pressure drop readings, the value of pressure drop for each of the phase flowing alone at the same flow rate as in two phase was also obtained under the same temperature conditions.

In a similar way the pressure drop information is obtained for different temperatures. It is important to observe that flow is stratified and flow rates of both the phases are such that Reynold number is greater than 2000. An attempt was made to keep the flow rates of both the phases same at different temperatures.

C. Observations:

As the effect of temperature on pressure gradient of two immiscible liquids - water and kerosene - was studied, the viscosities and densities are required at different temperatures. The specific gravity was measured with the help of 5 ml. specific gravity bottle at the liquid temperatures of 20°C, 30°C, 40°C and 50°C. The values of viscosities for both oil and water were obtained by nomograph[10] at the above required temperatures. Values of both viscosity and density are given in Appendix A.

Experimental data obtained under various conditions are shown in the Tables I, II, III and IV.

TABLE I

Temperature = 20°C

ΔH_{TP} = Two phase pressure drop as height of Ccl_4 in manometer

ΔH_M = Pressure drop as height of Ccl_4 in manom
when oil is flowing alone.

ΔH_L = Pressure drop as height of Ccl_4 in manometer when water is flowing alone.

Sl. No.	Oil flow rate gm./sec.	Water flow rate gm./sec.	Bypass valve position Oil	Water	ΔH_{TP} Cms.	ΔH_M Cms.	ΔH_L Cms.	Type of flow
1.	95.5	155	1 turn	1½ turn	18.45	6.50	9.8	stratified
2.	95.5	76.5	1 turn	1 turn	12.46	6.50	4.5	stratified
3.	84.0	76.5	open	1 turn	13.20	7.60	4.5	stratified
4.	95.5	65	1 turn	½ turn	10.90	6.50	3.4	stratified
5.	84.0	63.0	open	open	9.55	7.60	2.05	stratified
6.	146.0	63.0	2 turns	open	18.10	15.10	3.7	stratified

[illegible]

Temperature = 30°C

ΔH_{TP} = Two phase pressure drop as height of CCl_4 in manometer.

ΔH_M = Pressure drop as height of CCl_4 in manometer when oil is flowing alone.

ΔH_L = Pressure drop as height of CCl_4 in manometer when water is flowing alone.

Oil flow rate gm./sec.	Water flow rate gm./sec.	Bypass valve position Oil	Bypass valve position Water	ΔH_{TP} Cms.	ΔH_M Cms.	ΔH_L Cms.	Type of flow
83.5	157	open	1½ turn	18.0	6.5	10.7	Stratified
95.0	157	1 turn	1½ turn	22.0	7.1	10.7	
83.5	76.6	open	1 turn	12.25	6.5	5.0	Stratified
95.0	76.6	1 turn	1 turn	12.30	7.1	5.0	Stratified
83.5	65.0	open	½ turn	10.40	6.5	3.7	Stratified
86.5	64.15	½ turn	open	12.40	6.7	3.6	Stratified
95.0	65.0	1 turn	½ turn	12.45	7.1	3.69	Stratified
83.5	64.15	open	open	8.8	6.5	2.2	Stratified
95.0	76.6	1 turn	1 turn	12.35	7.1	2.2	Stratified
148.0	76.6	2 turns	1 turn	22.0	16.6	4.9	Stratified

TABLE III

Temperature = 40°C

ΔH_{TP} = Two phase pressure drop as height of Ccl_4 in manometer.

ΔH_M = Pressure drop as height of Ccl_4 in manometer when oil is flowing alone.

ΔH_L = Pressure drop as height of Ccl_4 in manometer when water is flowing alone.

Sl. No.	Oil flow rate gm./sec.	Water flow rate gm./sec.	Bypass valve position Oil	Bypass valve position Water	ΔH_{TP} Cms.	ΔH_M Cms.	ΔH_L Cms.	Type of flow
1.	83.0	150.0	open	1½ turn	24.7	8.25	10.6	Stratified
2.	94.0	75.0	1 turn	1 turn	15.3	7.05	4.95	Stratified
3.	83.0	75.0	open	1 turn	15.2	7.05	4.4	Stratified
4.	94.0	65.3	1 turn	½ turn	13.25	7.05	3.7	Stratified
5.	83.0	65.3	open	½ turn	12.75	8.25	3.7	Stratified
6.	85.2	63.9	½ turn	open	10.7	7.05	2.2	Stratified
7.	83.0	63.9	open	open	10.8	7.50	2.0	Stratified

TABLE IV

Temperature = 50°C

ΔH_{TP} = Two phase pressure drop as height of Col_4 in manometer.

ΔH_M = Pressure drop as height of Col_4 in manometer when oil is flowing alone.

ΔH_L = Pressure drop as height of Col_4 in manometer when water is flowing alone.

Sl. No.	Oil flow rate gm./sec.	Water flow rate gm./sec.	Bypass valve position Oil	Bypass valve position Water	ΔH_{TP} Cms.	ΔH_M Cms.	ΔH_L Cms.	Type of flow
1.	83.5	139.5	open	1½ turn	20.2	5.2	10.4	Stratified
2.	83.5	94.4	open	1 turn	12.95	5.2	4.2	Stratified
3.	83.5	75.4	open	½ turn	12.45	5.2	4.1	Stratified
4.	95.5	94.4	1 turn	1 turn	13.45	5.6	4.2	Stratified
5.	95.5	75.4	1 turn	½ turn	12.7	5.6	4.1	Stratified
6.	83.5	69.5	open	open	11.7	5.2	3.5	Stratified
7.	95.5	69.5	1 turn	open	12.2	5.6	3.5	Stratified
8.	85.5	69.5	½ turn	open	11.3	5.4	3.5	Stratified
9.	148.0	94.4	2 turns	1 turn	28.1	18.7	4.2	

CHAPTER IV

RESULTS AND DISCUSSIONS OF RESULTS

Lockhart and Martinelli[7] proposed a method of representing data for the flow of liquid gas mixtures in a horizontal pipe based on two parameters ϕ^2 and X^2. These parameters can be generalized, if the phases were considered as more viscous and less viscous. Thus ϕ_M^2 is ratio of two phase pressure gradient to the pressure gradient for more viscous fluid flowing alone and similarly ϕ_L^2 is defined for less viscous phase and X^2 is defined as a ratio of pressure gradient for more viscous flowing alone to the pressure gradient for the less viscous flowing alone. These parameters are obtained for various temperatures (20°C, 30°C, 40°C and 50°C) and the calculated values of ϕ_M^2, ϕ_L^2 and X^2 for various runs in stratified turbulent-turbulent regime are shown in Tables V, VI, VII and VIII. Sample calculations are shown in Appendix C.

TABLE V

Temperature = 20°C

$(\Delta P)_{TP}$ = Two phase pressure drop ; $(\Delta P)_M$ = More viscous phase pressure gradient when flowing alone, (oil).

$(\Delta P)_L$ = Pressure gradient for less viscous flowing alone, (water).

Sl. No.	Re_{oil}	Re_{water}	$(\Delta P)_{TP}$ gm./cm.^{2}	$(\Delta P)_M$ gm./cm^2	$(\Delta P)_L$ gm./cm^2	ϕ_M^2	ϕ_L^2	X^2
1.	3720	11530	11.02	3.87	5.87	2.85	1.88	0.664
2.	3720	5900	7.25	3.87	2.67	1.875	2.52	1.47
3.	3280	5900	7.9	4.53	2.67	1.745	2.96	1.69
4.	3720	5000	6.39	3.87	2.02	1.65	3.16	1.92
5.	3280	4850	5.7	4.53	1.2	1.26	4.75	3.76
6.	5630	4850	10.8	9.03	2.2	1.2	4.92	4.1

TABLE VI

Temperature = 30°C

$(\Delta P)_{TP}$ = Two phase pressure gradient ; $(\Delta P)_M$ = Pressure gradient for more viscous flowing alone, (oil).

$(\Delta P)_L$ = Pressure gradient for less viscous flowing alone, (water).

Sl. No.	Re_{oil}	Re_{water}	$(\Delta P)_{TP}$ gm./cm.^{2}	$(\Delta P)_M$ gm./cm^2	$(\Delta P)_L$ gm./cm^2	ϕ_M^2	ϕ_L^2	X^2
1.	3380	15700	10.8	3.9	6.42	2.76	1.69	0.606
2.	3850	15700	13.2	4.26	6.42	3.10	2.03	0.664
3.	3380	7670	7.36	3.9	2.99	1.86	2.46	1.34
4.	3850	7670	7.375	4.26	2.99	2.1	3.15	1.45
5.	3380	6510	6.25	3.90	2.2	1.6	2.85	1.76
6.	3500	6420	7.45	2.02	2.16	1.85	3.44	1.865
7.	3850	6510	7.46	4.26	2.22	1.75	3.39	1.95
8.	3380	6420	5.27	3.9	1.32	1.35	3.99	2.96
9.	3850	7670	6.2	4.26	1.32	1.45	4.7	3.215
10.	6000	7670	13.2	9.96	2.9	1.38	4.75	3.38

TABLE VII

Temperature = 40°C

$(\Delta P)_{TP}$ = Two phase pressure gradient;

$(\Delta P)_{M}$ = Pressure gradient for more viscous flowing alone, (oil).

$(\Delta P)_{L}$ = Pressure gradient for less viscous flowing alone, (water).

Sl. No.	Re_{oil}	Re_{water}	$(\Delta P)_{TP}$ gm./cm.^{2}	$(\Delta P)_{M}$ gm./cm.^{2}	$(\Delta P)_{L}$ gm./cm.^{2}	ϕ_M^2	ϕ_L^2	X^2
1.	4060	18440	14.92	4.98	6.42	3.0	2.1	0.776
2.	4610	9220	9.25	4.26	2.99	2.16	2.82	1.45
3.	4060	9220	9.2	4.26	2.67	2.0	3.17	1.69
4.	4610	8360	8.01	4.26	2.22	1.88	3.47	1.95
5.	4060	8360	7.65	4.98	2.22	2.6	3.4	2.2
6.	4170	7850	6.47	4.26	1.32	1.52	4.8	3.215
7.	4060	7850	6.48	4.53	1.2	1.43	5.5	3.76

TABLE VIII

Temperature = 50°C

$(\Delta P)_{TP}$ = Two phase pressure gradient; $(\Delta P)_{M}$ = Pressure gradient for more viscous flowing alone, (oil).

$(\Delta P)_{L}$ = Pressure gradient for less viscous flowing alone, (water).

Sl. No.	Re_{oil}	Re_{water}	$(\Delta P)_{TP}$ gm./cm.^{2}	$(\Delta P)_{M}$ gm./cm.^{2}	$(\Delta P)_{L}$ gm./cm.^{2}	ϕ_M^2	ϕ_L^2	X^2
1.	4500	19000	12.2	3.16	6.32	3.9	1.93	0.5
2.	4500	12800	7.9	3.16	2.67	2.5	2.96	1.18
3.	4500	10200	7.6	3.16	2.55	2.4	2.98	1.24
4.	5150	12800	8.21	3.4	2.67	2.42	3.06	1.275
5.	5150	10200	7.75	3.4	2.55	2.28	3.04	1.335
6.	4500	9360	7.13	3.16	2.13	2.55	3.35	1.485
7.	5150	9360	7.41	3.4	2.13	2.18	3.48	1.6
8.	4620	9360	6.87	3.28	2.13	2.1	3.23	1.78
9.	8000	12800	17.1	11.4	2.67	1.5	6.4	3.9

Typical pressure gradient data was obtained in turbulent turbulent regime for the stratified flow of two immiscible liquids kerosene and water in a circular pipe. Pressure gradient is observed as a function of superfacial Reynold number of water or faster moving phase. The Reynold number was calculated using an equivalent diameter of 0.62 inch and superfacial phase velocity by dividing the phase velocity by the conduit cross-section area.

It is observed after analysing the data that pressure gradient is very high for low oil Reynold number and highw ater. Reynold number. It is concluded that this was due to more pronounced interfacial waves existing under these conditions. And at higher Reynold numbers of water it follows additive law while at high oil Reynold numbers and low water Reynold numbers it does not follow additive law and the two phase pressure gradient is reduced. As the more viscous phasc (oil) flows in an annulus. Assumption made for measuring the pressure gradient is that there is uniform pressure at the cross-section in a closed pipe.

The deviation from Lockhart and Martinelli[7] curve of parameters for laminar tubulent (oil-water) flow is 24% and in this case of turbulent turbulent flow the deviation in parameter is 60%. Therefore the Lockhart and Martinelli curves for liquid-gas turbulent-turbulent flow is compared with flow of two liquids (Fig. 3 & 4). Hence from the curves it is concluded that Lockhart and Martinelli curves are not valid for liquid-liquid system in turbulent regime. The two phase pressure gradient is less for turbulent as compared with two phase flow of two liquids in laminar turbulent flow.

Plots are prepared of ϕ_M^2 versus X^2 (Fig. 3) and ϕ_L^2 versus X^2 (Fig.4) with the help of Tables V, VI, VII and VIII. Lockhart and Martinelli parameters for gas liquid turbulent-turbulent flow are given in Appendix B and these values are also plotted in Fig.3 and Fig.4 for the comparison with experimentally obtained values for liquid-liquid stratified (turbulent-turbulent) flow at different temperatures.

It happens that for liquid-liquid flow, the data obtained for stratified flow consistently deviates considerably from Lockhart and Martinelli correlation as shown in Fig. 3 and Fig. 4. It is concluded that actual two phase pressure drop is being less than that predicted by Lockhart and Martinelli. At higher temperatures, it is observed that two phase pressure gradient is more near to the predicted values than pressure gradient at lower temperatures. As can be seen from Fig. 3 and Fig. 4, as we increase the temperature, the viscosity of liquid phases decreases, though to a small extent. Taking data at higher temperatures (which is not possible in the present case due to the hazardous nature of kerosene) would have shown that the liquid-liquid flow case would yield results similar to gas-liquid case, under conditions of low liquid viscosities. The Lockhart and Martinelli curves would then nearly represent the combined pressure drops.

In the present case, the effect of temperature on pressure gradient is not very large, a generalized curve of

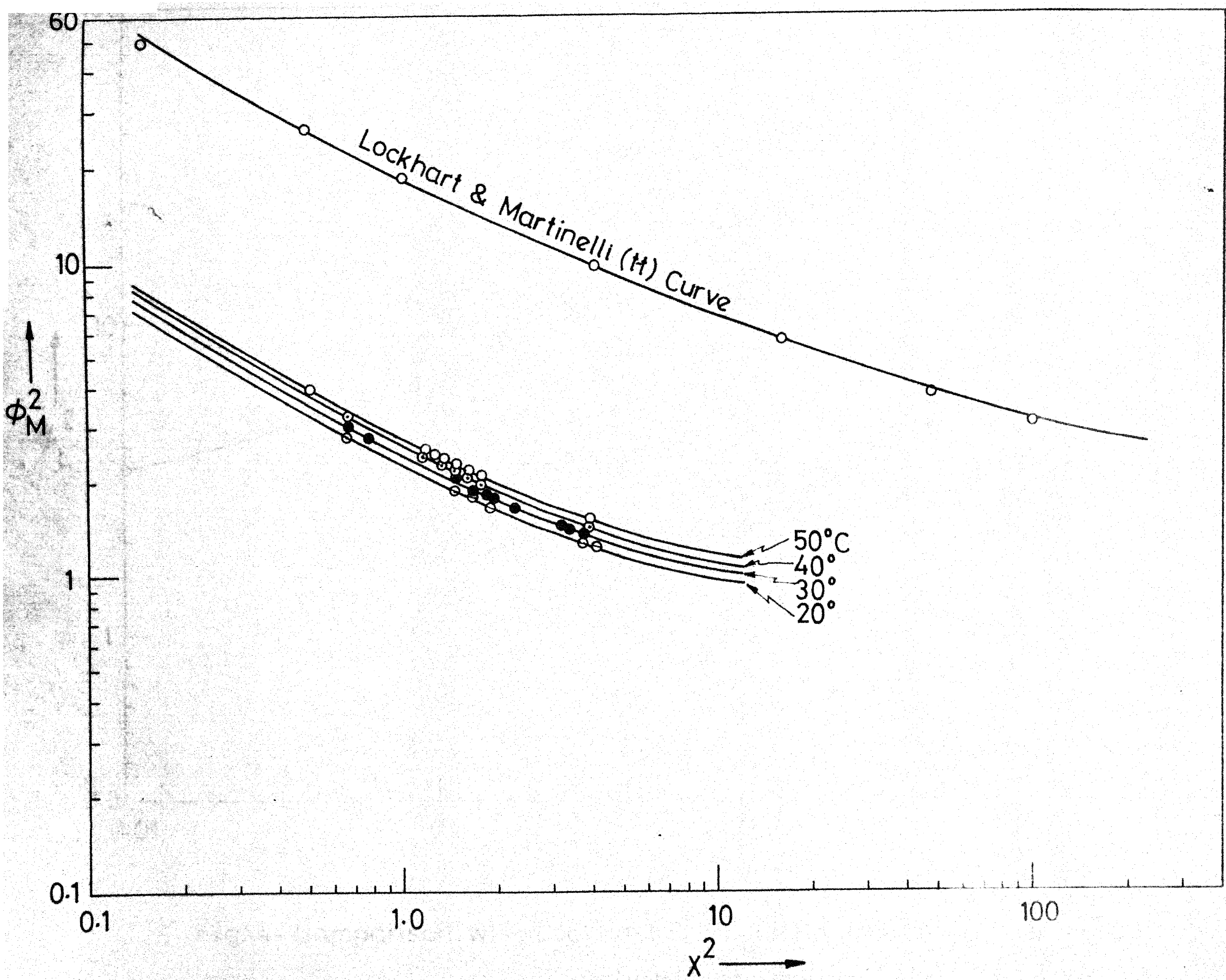

Fig. 3 - Comparison with Lockhart & Martinelli parameters for Turbulent-Turbulent flow.

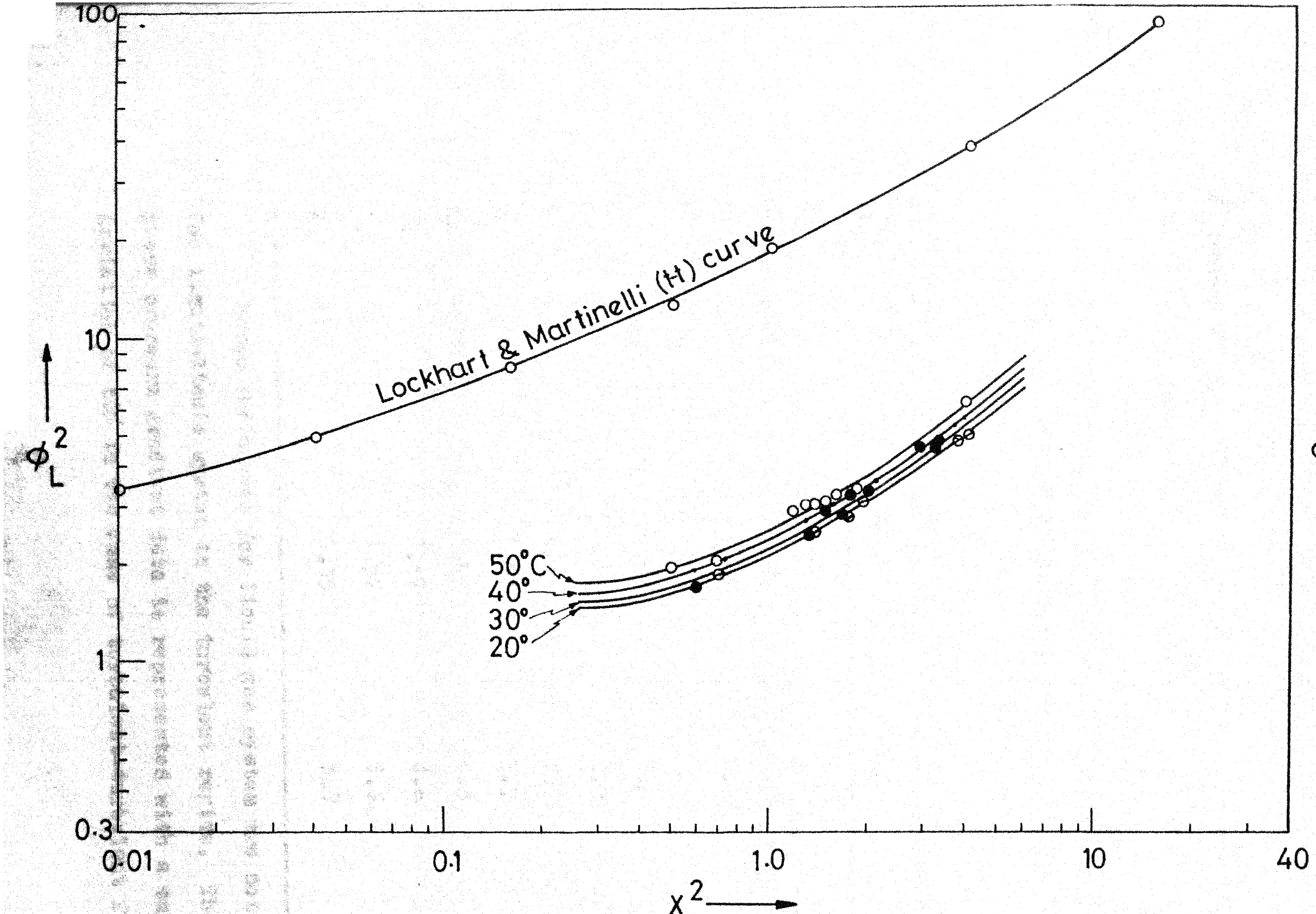

Fig. 4- Comparison with Lockhart & Martinelli parameters for Turbulent-Turbulent flow.

ϕ_M^2 versus X^2 (Fig. 5) and ϕ_L^2 versus X^2 (Fig. 6) are plotted using all the data available at different temperatures and fitting a polynomial using least square method.

TABLE IX

Values of Parameters for Generalized Curves
(Fig.5 & 6)

Sl. No.	X^2	ϕ_M^2	ϕ_L^2
1.	0.5	3.6	1.89
2.	0.67	2.98	1.95
3.	0.78	2.73	2.08
4.	1.18	2.3	2.5
5.	1.45	2.13	2.8
6.	1.6	2.0	3.05
7.	1.95	1.85	3.35
8.	2.28	1.67	3.7
9.	2.88	1.55	4.3
10.	3.2	1.47	4.6
11.	3.9	1.37	5.6
12.	4.1	1.35	5.7

Hence the curves for liquid gas system are not valid for liquid-liquid system in the turbulent regime. The two phase pressure gradient data is represented with a maximum deviation of 60% in the case of turbulent-turbulent flow.

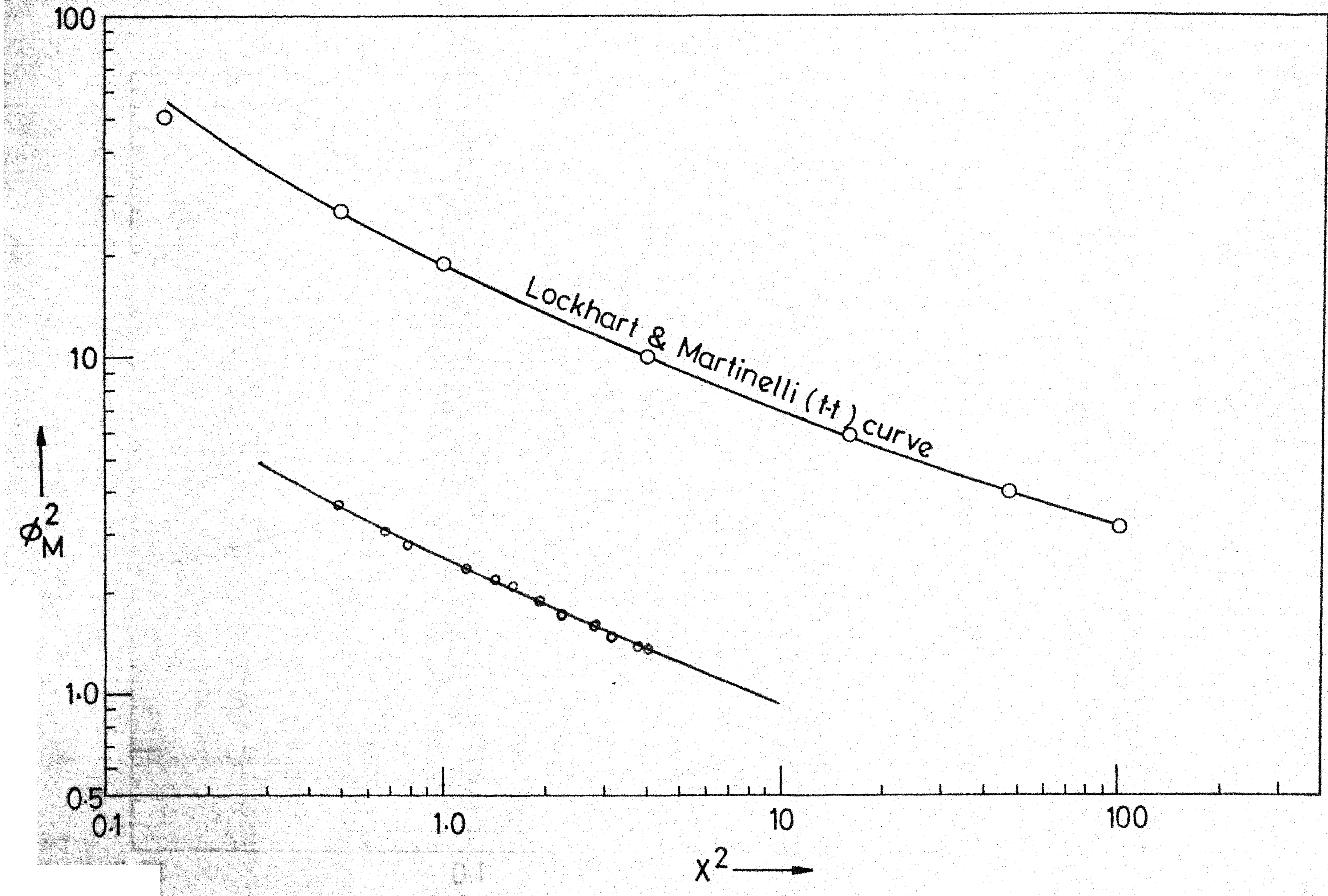

Fig. 5-Generalised plot of ϕ_M^2 vs. X^2 for Liquid-Liquid flow.

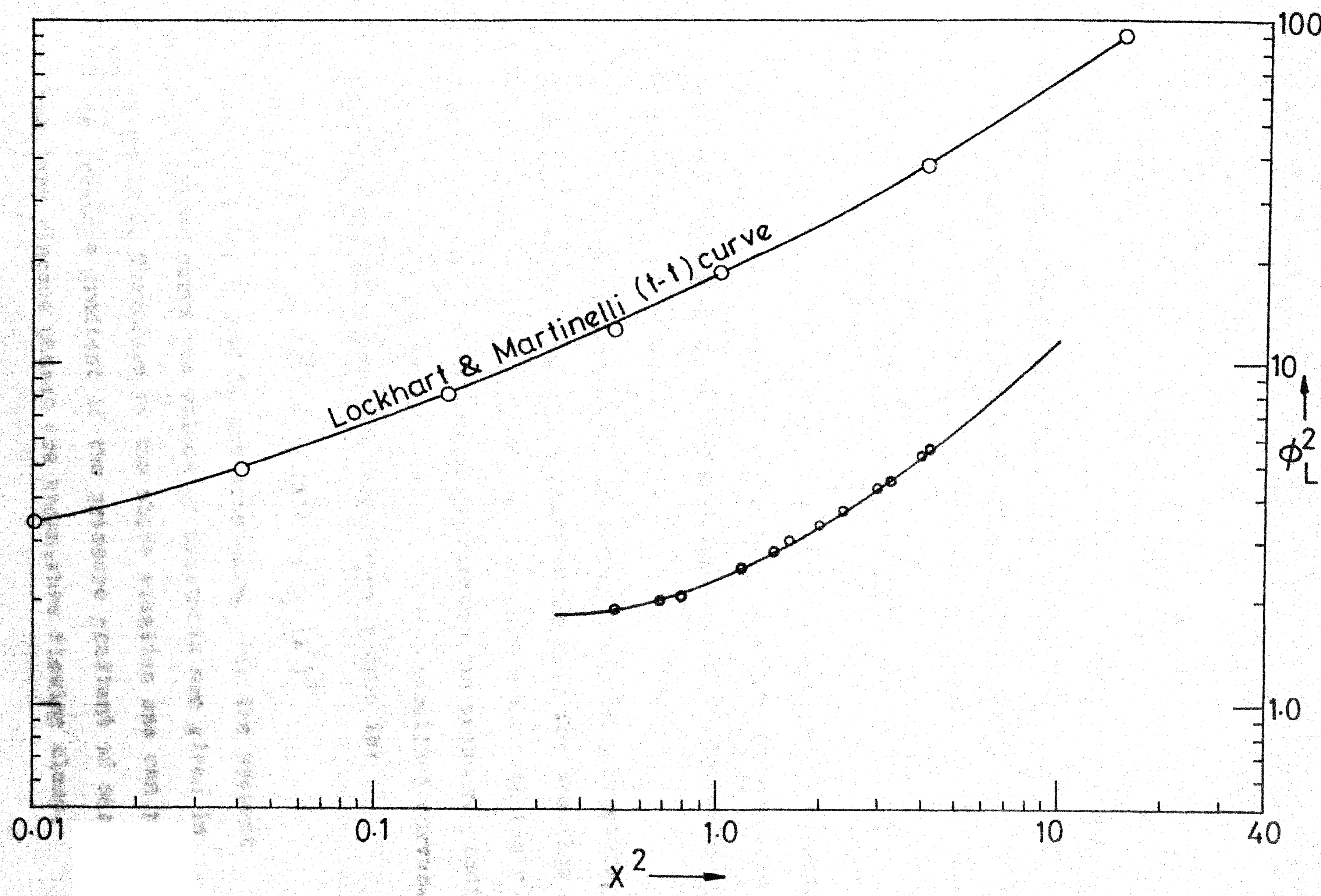

Fig. 6–Generalised plot of ϕ_L^2 vs. X^2 for Liquid-Liquid flow.

It is apparent therefore, that not only the ϕ_M^2 and ϕ_L^2 superimpose data for a particular system but also brings together data for widely different viscosity ratio and different temperatures. In Figures 3,4,5 and 6 it is observed that there is similar trend of curves for liquid-liquid flow with Lockhart and Martinelli's curves although there is considerable displacement.

This work in turbulent - turbulent regime is expected to be helpful to determine the extent to which the pressure gradient for the flow of a viscous phase may be reduced in presence of less viscous phase.

In conclusion, it would appear that the parameters, ϕ^2 and X^2, will be useful in correlating data for the flow of two immiscible liquids in a closed conduit when both the phases are turbulent. The effect of temperature on pressure gradient is also taken into consideration in the generalized curves. The equation for predicting the pressure drop is:

$$\phi_M^2 = B_0 + B_1\,(X^2) + B_2\,(X^2)^2 + B_3\,(X^2)^3$$

Where B_0, B_1, B_2 and B_3 are constants. For the present generalized curve the values of constants are given in Appendix C. Therefore by the above equation one can predict the pressure gradient if the pressure gradient of more viscous and less viscous phases are known, when flowing alone.

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REFERENCES

1. Charles, M.E., Govier, G.W., and Hodgson, G.W., Cand. Jour. of Chem. Engg., Feb., 27 (1961).

2. Charles, M.E. and Redberger, P.J., Cand. J. of Chem. Engg., April, 70 (1962).

3. Gemmell, A.R. and Epstein, N., Cand. J. of Chem. Engg., Oct., 215 (1962).

4. Charles, M.E. and Lilleleht, L.U., Cand. J. of Chem. Engg., June, 110 (1965).

5. Charles, M.E. and Lilleleht, L.U., J. of Fluid Mech., 22, Vol. 2, 217 (1965).

6. Charles, M.E., and Lilleleht, L.U., Cand. J. of Chem. Engg., Feb., 147, (1966).

7. Lockhart, R.W. and Martinelli, R.C., C.E.P., Vol.45, No.1, 39 (1949).

8. Dukler, A.E., Wicks, M., and Cleveland, R.G., A.I.ChE. J., Vol. 10, No.1, 38 (1964).

9. Darby, Ron, and Akers, W., A.I.Ch.E.J., Vol. 12, No.5, 999 (1966).

10. Perry, J.H. Chief Editor, Chemical Engg. Hand Book, 4th Ed. pp.319, (1964).

11. Hanratty, T.J. and J.M. Engen, A.I.Ch.E.J., 3, 299 (1957).

12. Shearer, C.J., and R.M. Nedderman, Chem. Eng. Sci., 20, 671 (1965).

13. Isaacs, J.D. and Speed, J.B., U.S. Patent 759374 (1904).

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APPENDIX A

Specific Gravity and Viscosities of Kerosene and Water at Different Temperatures

Temperature °C	Kerosene		Water	
	Specific gravity	Viscosity cp	Specific gravity	Viscosity cp
20	0.82	2.4	0.998	1.054
30	0.815	2.0	0.995	0.8007
40	0.813	1.65	0.990	0.6560
50	0.81	1.38	0.985	0.5494

Viscosities of both water and kerosene from nomographs (10).

Density of carbontetrachloride = 1.595 gm./cm^3(monometer liquid).

* * *

APPENDIX B

Lockhart and Martinelli Parameters for Turbulent-Turbulent Regime (Ref.7)

ϕ_M^2	ϕ_L^2	X^2
344.0	3.41	0.01
125.6	4.98	0.04
49.5	8.00	0.16
25.4	12.40	0.49
18.6	18.6	1.00
9.6	38.6	4.00
5.65	90.0	16.00
3.85	118.6	49.00
3.06	305.0	100.00

* * * *

APPENDIX C

SAMPLE CALCULATION

Table I   Temperature 20°C

Reading No.1

Oil flow rate = 95.5 gm/sec.

Water flow rate = 65 gm/sec.

Reynold No. Re = $\frac{DU\rho}{\mu} = \frac{GD}{\mu}$

where D - diameter of tube in cms.

G - Flow rate per unit area per second (gm./cm^2.sec.)

μ - Viscosity (poise)

Therefore oil Re $= \frac{95.5 \times 1.575 \times 4}{(1.575)^2 \times 2.4 \times 10^{-2}}$

$= 3720.$

Water Re. $= \frac{65 \times 1.575 \times 4}{(1.575)^2 \times 1.05 \times 10^{-2}}$

$= 5000$

Ccl$_4$ Manometer Readings:

ΔH_{TP} = Two phase pressure drop as height of Ccl$_4$ in manometer = 18.5 cms.

ΔH_M = Pressure drop as height of Ccl$_4$ in manometer when oil is flowing alone = 6.5 cms.

ΔH_L = Pressure drop as height of Ccl$_4$ in manometer when water is flowing alone = 9.8 cms.

Therefore $(\Delta P)_{TP} = \Delta H(\rho_B - \rho_A)$ where ρ_A = Density of water

$= 18.5\ (1.595 - 0.998)$ ρ_B = Density of CCl_4

$= 11.02\ gm/cm^2$

$$(\Delta P)_M = 6.5\ (1.595 - 0.998)$$
$$= 3.87\ gm/cm^2.$$
$$(\Delta P)_L = 9.8\ (1.595 - 0.998)$$
$$= 5.87\ gm/cm^2$$

Lockhart and Martinelli Parameters are calculated as follows:

$$\phi_M^2 = \frac{(\Delta P)_{TP}}{(\Delta P)_M} = \frac{11.02}{3.87} = 2.85$$

$$\phi_L^2 = \frac{(\Delta P)_{TP}}{(\Delta P)_L} = \frac{11.02}{6.87} = 1.88$$

$$X^2 = \frac{(\Delta P)_M}{(\Delta P)_L} = \frac{3.87}{5.87} = 0.664$$

Similarly the parameters are calculated for individual reading at one temperature and readings at different temperatures. For Each set of readings a polynomial is fitted which also satisfies Lockhart and Martinelli parameters (Appendix B) with the help of Computer (Fig.3 & 4). Same polynomial is fitted for the parameters for the generalised curve (Fig. 5 & 6).

The polynomial for predicting the value of ϕ_M^2 and ϕ_L^2 are as follows:

$$\phi_M^2 = B_0 + B_1(X^2) + B_2(X^2)^2 + B_3(X^2)^3$$

and $\phi_L^2 = B_0' + B_1' (X^2) + B_2' (X^2)^2 + B_3' (X^2)^3$

The value of constant are as follows:

$$B_0 = 4.6295$$

$$B_1 = -2.9695$$

$$B_2 = 1.0471$$

$$B_3 = -0.1293$$

and

$$B'_0 = 0.9191$$

$$B'_1 = 1.9647$$

$$B'_2 = -0.4918$$

$$B'_3 = 0.0721$$

* * * * *